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ABSTRACT

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Tests were performed at velocities of 15,500 ft/sec in the Ballistic Range of the Naval Ordnance Laboratory (NOL) in order to determine the effects of carbon dioxide on aerodynamic characteristics. Two configurations were tested; both were spherically-blunted cones with flat bases. The resultant aerodynamic data indicate no appreciable effect on drag and stability due to carbon dioxide. They correlated well with existing information obtained at lower Mach numbers and show a slight decrease in stability with increasing Mach number. Author

I. INTRODUCTION

The probability that the Mars and Venus atmospheres contain substantial amounts of carbon dioxide increases the complexity of designing vehicles capable of entering the atmospheres of these planets. In order to assay the effect on aerodynamic forces and moments of varying amounts of carbon dioxide and nitrogen mixtures at very high velocities, a ballistic range program was conducted at the Naval Ordnance Laboratory, White Oak, Maryland.* A secondary purpose of the program was to obtain aerodynamic data in the hypersonic regime. This program was conducted during the months of December 1962 and January 1963.

*A NOL data report is forthcoming.

II. TEST OPERATION

Two configurations were tested. Each of these had spherically blunted conical bodies with flat bases. The *A*-1 designated configuration was the more blunt of the two and had a nose radius-to-base diameter of 0.545, and a 10-deg cone angle (half angle). The *V*-1 configuration had a nose radius-to-base diameter of 0.250 and a 15-deg cone angle. The configurations are shown in Fig. 1. The test was performed with 0.5-in. dia. steel models. An *A*-1 configuration model and lanching sabot are shown in Fig. 2. The test was performed at a range pressure of about 90mm of mercury. The Reynolds numbers based on the maximum diameter were nominally 0.5×10^6.

The program was conducted in the NOL Pressurized Ballistic Range No. 3, which has a flight path of approximately 170 ft. During flight, a model passes 27 spark shadowgraph stations where the translational position and attitude are recorded in the horizontal and vertical planes. Figs. 3 and 4 show a typical pair of shadowgraphs from the test. The models were launched with a two-stage, light-gas gun. Initially, it was desired to achieve velocities in the order of 18,000 ft/sec. However, this proved too difficult to obtain without time for further development and, of necessity, the velocity was reduced to nominally 15,500 ft/sec.

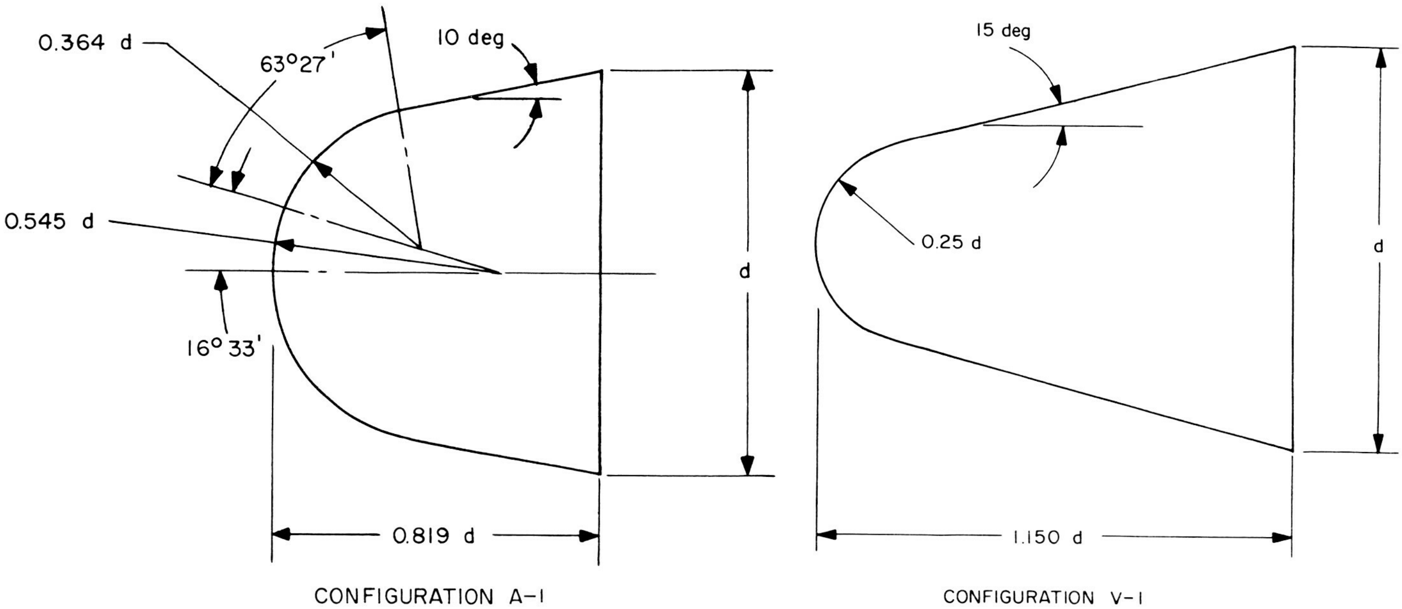

Fig. 1. Model geometry, Configurations *A*-1 and *V*-1

The gas composition was measured at three different stations in the range with a gas chromatograph and, in addition, samples were taken to the Bureau of Standards in Washington, D. C. for mass spectrometric analysis. The measurements usually fell in a band of $\pm 2\%$. The nominal Mach number for air or high-content nitrogen rounds was about 13.5; the nominal Mach number for the high-content carbon dioxide rounds was 16.5. The speed of sound was measured experimentally at two stations in the range by means of a sound disturbance source and two pairs of oscilloscope pickups. The deviation between the readings was less than 0.5%.

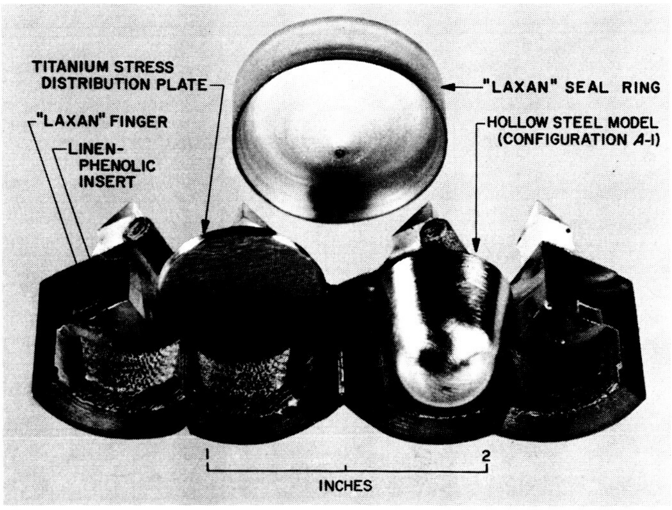

Fig. 2. Configuration *A*-1 model and launching sabot

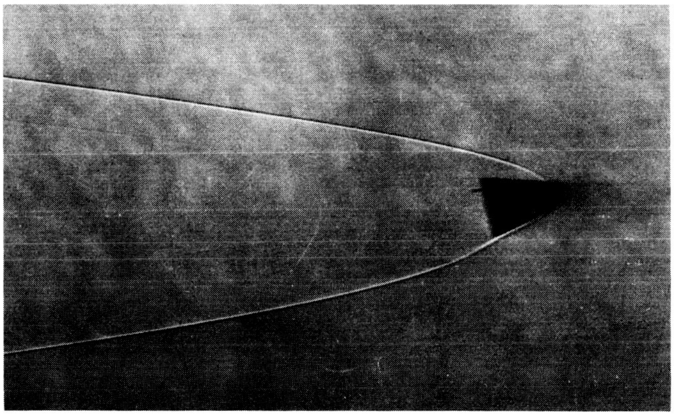

Fig. 3. Shadowgraph history at Station 16, vertical plane

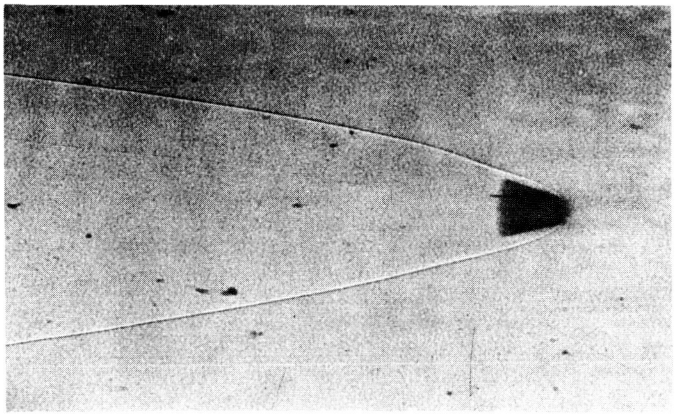

Fig. 4. Shadowgraph history at Station 16, horizontal plane

III. DATA REDUCTION

Drag coefficients were obtained from the translational histories of the models. A cubic least-squares fit relating time and distance was performed on the data and from the resultant smoothed relationship, drag was extracted. Stated accuracies are generally much better than 0.5% for a single shot. However, correlation of many shots does not verify this; a more realistic value is about 1%.

Stability derivatives were obtained from flight attitude histories of the models. A tricyclic equation in the complex plane, of the form

$$\beta + i\alpha = K_1 e^{(\lambda_1 + i\varphi_1)x} + K_2 e^{(\lambda_2 + i\varphi_2)x} + K_3 e^{ipx}$$

was fitted to the data where x is the translational position of the model, and α and β are the angular projections on the vertical and horizontal planes. $\lambda_{1,2}$ produce the motion damping, $\phi_{1,2}$ produce the pitching motion, and the last term accounts for non-zero angle-of-attack trim angles. The effective pitching moment slope is $-C_{m_\alpha} = \dfrac{2\phi_1\phi_2 I}{\rho A d}$. Figure 5 shows the original set of data from a typical shot and a plot of the fit equation. The probable error in measuring the angles is in the order of one degree.

The accuracy of the stability data fell into two categories; data where the probable error was in the order of less than 5%, and data where the probable error was in the order of 20%. The wide deviation was generally caused by the inability to obtain model attitude at a sufficient number of stations. This was often attributed to the extreme luminosity of the high-velocity models, which caused fogging of photographs and occasional premature firing of the shutter system. For the analysis of drag and stability presented herein, only the first group of data is used.

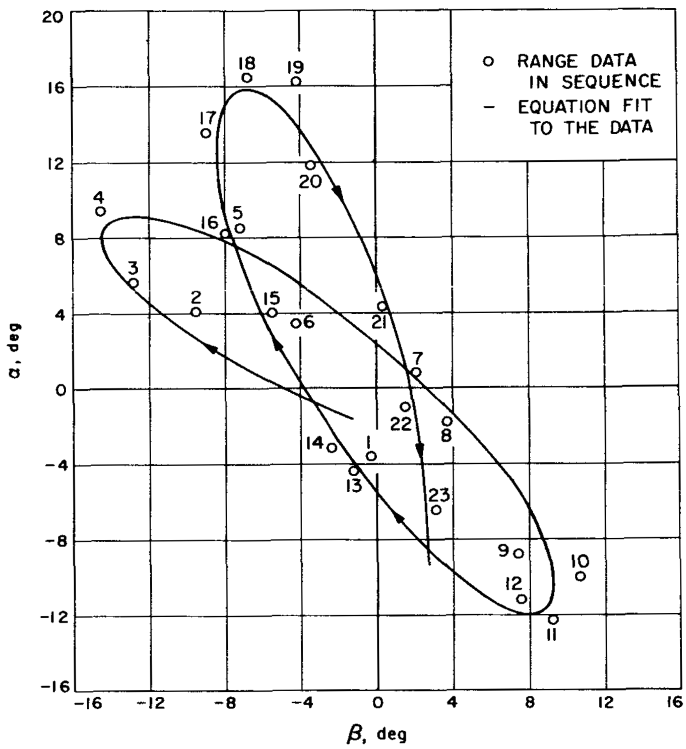

Fig. 5. α, β trace of round 4882

IV. DATA ANALYSIS

Before any comparison of the stability derivatives can be performed, the experimental stability derivatives must be referenced to the same center-of-gravity location. This, of course, necessitates knowing the normal force coefficient, C_{N_α}. For a body of low lift, such as the A-1 configuration, obtaining this information from range swerving motion is subject to excessive error since the swerving motion will be small. In order to determine the most valid value of C_{N_α} for Configuration A-1, wind tunnel data (Ref. 1) from Mach 3 to Mach 8 (air), as well as a mean value from the range data (air and nitrogen shots) were compared (Fig. 6). From this plot, a C_{N_α} value of 0.0176/deg was chosen, and the Configuration A-1 data were transformed to a center-of-gravity location 0.482 diameters aft of the nose. Estimates of the error in the center-of-pressure position that might have occurred by using the improper C_{N_α} are in the order of 0.1% of the base diameter. This is due to the fact that the experimental center-of-gravity was very close to 0.482 diameters in all cases. The range C_{N_α} data for Configuration V-1 were subject to fewer errors since this configuration has a larger lift force, resulting in larger swerve motions. The data ranged from 0.021/deg to 0.025/deg and indicated a possible trend toward an increase in normal force with large percentages of carbon dioxide; the stated probable errors were in the order of 0.001/deg to 0.002/deg. A mean value of 0.023/deg was used to transform the stability derivatives. The transformation errors were again kept at a minimum by choosing the reference center-of-gravity (0.676 dia. aft of nose) close to the physical center-of-gravity.

The drag and stability data are best correlated with the mean-square resultant angle-of-attack, δ^2, which is defined as

$$\delta^2 = \frac{\int_0^x (\eta^2)\,dx}{x}$$

where $\eta = \sqrt{\alpha^2 + \beta^2} \equiv$ resultant angle-of-attack.

It has been shown that if a body has local drag and pitching moment coefficients of the form

$$C_D = C_{D_0} + k\eta^2 \text{ and } C_m = C_{m_{\alpha_0}}\eta + K\eta^3,$$

then C_{D_e}, the effective constant drag coefficient, and C_{m_α}, the effective linear pitching moment slope, are essentially linear functions of δ^2. Consider the effective drag during flight:

$$C_{D_e} \int_0^x dx = \int_0^x C_D\,dx \qquad \text{or,}$$

$$C_{D_e} = \frac{\int_0^x (C_{D_0} + k\eta^2)\,dx}{x}$$

$$= C_{D_0} + \frac{k\int_0^x (\eta^2)\,dx}{x} = C_{D_0} + k\delta^2$$

Therefore, fitting a straight line through the C_{D_e} vs δ^2 data will yield the constant "k" applicable in the local drag equation.

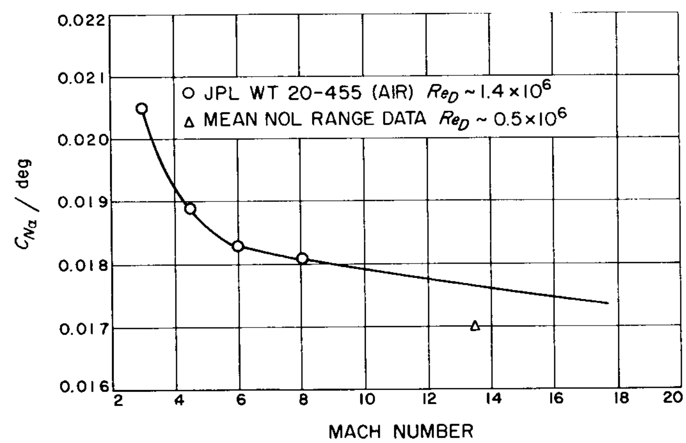

Fig. 6. C_{N_α} vs Mach number for Configuration A-1

The analysis of a cubic pitching moment was considered by Rasmussen (Ref. 2). He showed that for a pitching moment that grows faster than a linear pitching moment, an effective pitching moment slope is given by the following expression:

$$\left(\frac{\rho A d}{2I}\right) C_{m_\alpha} = K_1 + K_2(\eta^2_{max} + \eta^2_{min})$$

The applicability of this equation to free-flight data of Configuration A-1 was verified at Mach 3.5 and Mach 8.5 (Ref 3).

The term $\frac{\rho A d}{2I}$ is dependent upon the test gas density and the model geometry; generally, it will not vary appreciably from round to round. The term $(\eta^2_{max} + \eta^2_{min})$ is approximately equal to $2\delta^2$. Therefore,

$$C_{m_a} \approx C_{m_{a_0}} + K\delta^2$$

A. A-1 Configuration

A-1 configuration drag data are shown plotted in Fig. 7 as a function of δ^2. A straight line was faired through the data, and the deviation from this line is in the order of one percent. From the plot, there appears to be no discernible effect on drag due to the presence of carbon dioxide. The drag, as a function of angle-of-attack corresponding to the faired line, is

$$C_D = 0.705 + 0.0167 \times 10^{-2}\,\eta^2$$

where η is in deg. C_D corresponding to this equation is shown in Fig. 8 along with wind tunnel data at Mach 4.54 (Ref. 4) for the A-1 configuration with a 50-deg half angle cone base. The deviation between these curves is about 0.5%.

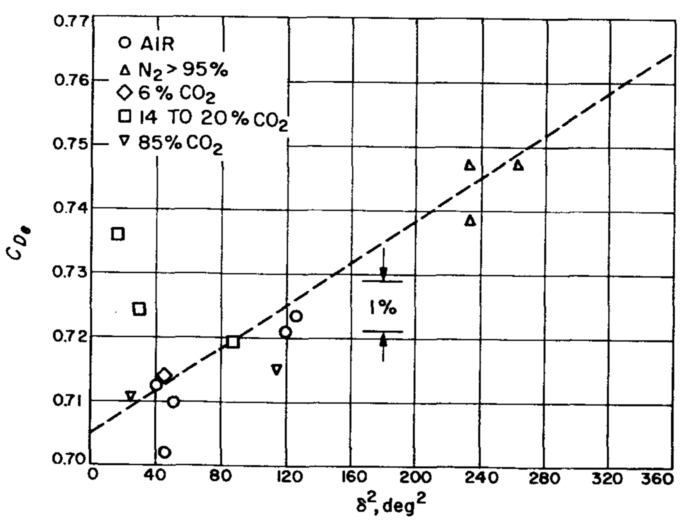

Fig. 7. Range drag data, Configuration A-1

A preliminary examination of the stability data indicates that the high-content nitrogen data (nitrogen > 95% of total) and air data can be considered one family; no trends due to the slight differences in their gas compositions are apparent. The stability derivatives of this type of data are shown in Fig. 9 as a function of δ^2. A straight line was faired through the data and all except one point fell within ±0.25% diameter center-of-pressure deviation. The data obtained in high-content carbon dioxide are shown in Fig. 10 along with the mean faired line from Fig. 9. With the exception of Round 4905, all data indicate slightly less stability; this decrease, however, is in all cases, much less than one percent diameter center-of-pressure shift. A closer examination of Round 4905 indicated that the model had a trim angle of about 8 deg, and experienced extreme nonsymmetrical

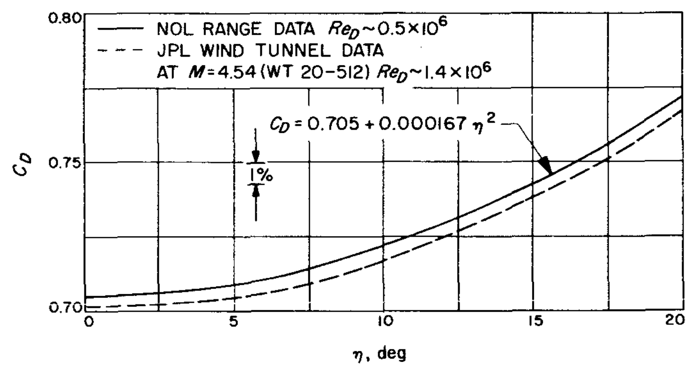

Fig. 8. Comparison of wind tunnel and range drag data, Configuration A-1

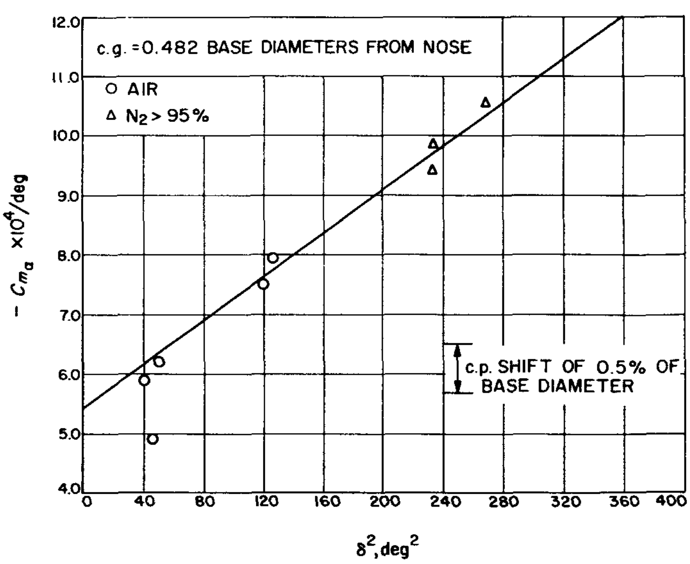

Fig. 9. Pitching moment slope for air and rounds where N_2 > 95%, Configuration A-1

motion. The attempt to correlate this data with δ^2 is not applicable in this situation.

Figure 11 is a plot of the center-of-pressure location vs Mach number, obtained from existing wind tunnel and ballistic range data in air or high nitrogen composition. As a basis of comparison, the mean pitching moment slope through the angle-of-attack range of 0 to 12 deg was used to determine the center-of-pressure location rather than the slope through zero angle-of-attack. The reason for this is that the wind tunnel data are nonlinear in the angle-of-attack region near zero. The data from this test correlated well with the existing data (Refs. 1 and 3). This summary plot (Fig. 11) indicates a slight center-of-pressure shift toward instability with increasing Mach number of about a one percent diameter from Mach 8 to 14.

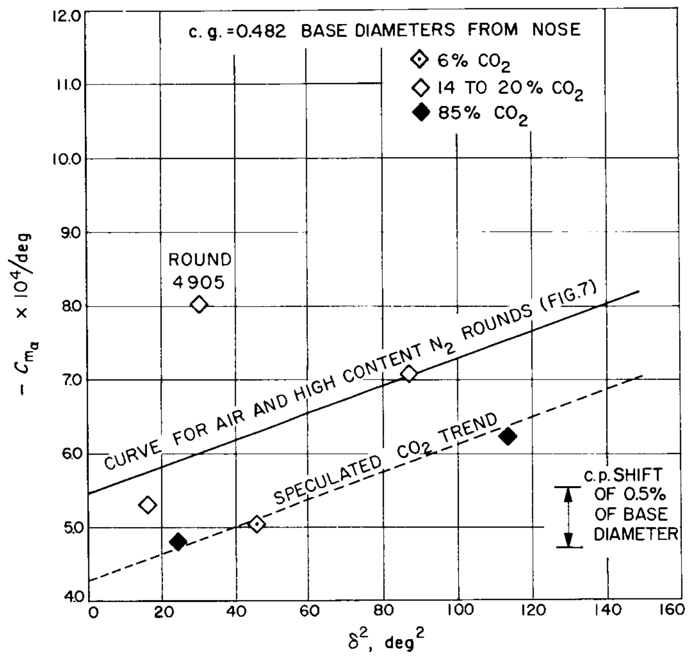

Fig. 10. Pitching moment slope for CO_2 rounds, Configuration A-1

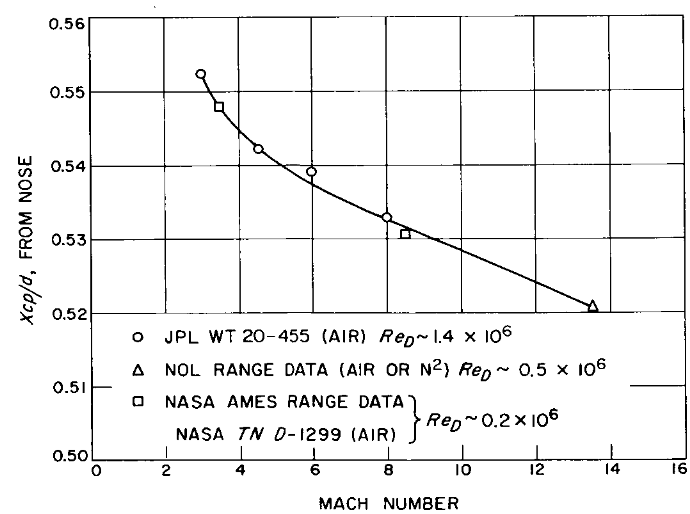

Fig. 11. Center-of-pressure data, Configuration A-1

B. V-1 Configuration

The drag and stability data for Configuration V-1 are plotted on Figs. 12 and 13 as functions of δ^2. The drag, corresponding to a faired straight line of the data, is

$$C_D = 0.332 + 0.0593 \times 10^{-2} \eta^2$$

The deviation from this mean line is in the order of $\pm 2\%$. As a means of comparison, the drag coefficient corresponding to the equation is plotted on Fig. 14 along with the modified Newtonian prediction of drag. In general, the agreement is quite good. The deviation between the curves becoming substantial only at the higher angles-of-attack when the form of the drag equation is somewhat in question.

Excluding one data point, Round 4874, the stability derivatives lie within a band 2% of the diameter center-

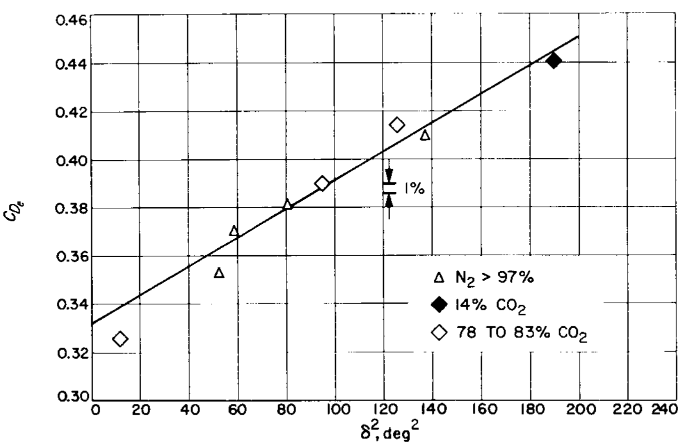

Fig. 12. Drag data, Configuration V-1

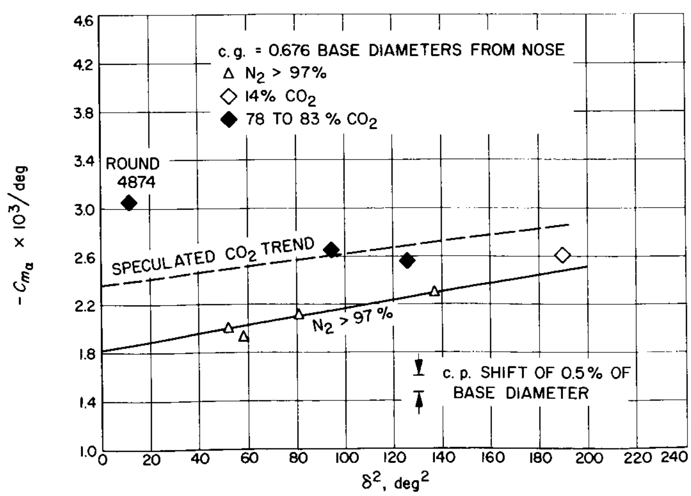

Fig. 13. Stability data, Configuration V-1

of-pressure deviation. This band (-1.8×10^{-3} to -2.4×10^{-3}) of pitching moment slopes agrees well with the modified Newtonian predicted value, at zero angle-of-attack, of -2.0×10^{-3}/deg. The high-content nitrogen and air round data, as a group, lie on a common straight line within 0.5% diameter center-of-pressure deviation. Although there were only a few rounds of substantial amounts of carbon dioxide (not enough to make a firm judgment) these data do indicate a possible tendency toward a slight increase in stability.

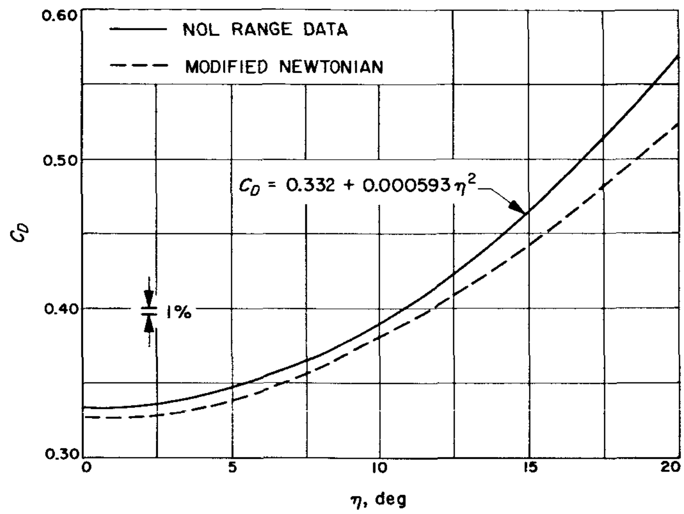

Fig. 14. Comparison of modified Newtonian and range data, Configuration V-1

V. CONCLUSION

The results show that perceptively, only small changes in the aerodynamic drag and moment coefficients occur when firing in substantial amounts of carbon dioxide. There was no apparent change of the drag coefficients. However, there were trends indicating that the stability derivatives were somewhat affected; the *A*-1 configuration pitching moment became slightly less stable, the *V*-1 configuration pitching moment became slightly more stable.

The *A*-1 configuration drag and stability data correlated well with existing range and wind tunnel data taken at lower Mach numbers. The summary plot of the center-of-pressure location indicates that the center-of-pressure moves slightly toward the direction of instability with increasing Mach number.

NOMENCLATURE

A maximum cross sectional area of model, $\frac{\pi d^2}{4}$

C_D drag coefficient, based on A

C_{m_α} effective pitching moment slope coefficient, based on A and d, per degree; also, stability derivative

C_{N_α} normal force slope coefficient, based on A, per degree

d maximum model diameter, i.e., base diameter

I model moment-of-inertia about a traverse axis through the center-of-gravity

p roll rate

Re_d Reynolds number based on d

x translational position of model down range

α projection of model attitude on a vertical plane parallel to range axis

β projection of model attitude on a horizontal plane parallel to range axis

δ^2 mean-squared resultant angle-of-attack, $\frac{\int_0^x (\eta^2)\, dx}{x}$

η $\sqrt{\alpha^2 + \beta^2}$

$\lambda_{1,2}$ damping parameters

ρ gas density

$\phi_{1,2}$ pitching motion parameters

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